Experimental and Theoretical Study of Strata Formation in Sedimentary Basins

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LONG TERM GOALS

A major goal of our stratigraphy project is to obtain experimental evidence and to develop quantitative models of the formation of strata on continental margins. Experiments and analytical models can greatly contribute to bridge the gap between variation in forcing functions such as sediment supply, sea-level changes and subsidence, and the resulting stratigraphy in depositional basins, and therefore allow for (1) inferring the history of external forcing from preserved strata (inversion problem) or (2) predicting the nature of preserved strata in areas where the forcing history is known. By applying techniques from geophysics and engineering to stratigraphic problems, we are also helping to convert stratigraphy from a purely descriptive to a more quantitative, analytical science.

OBJECTIVES

Our objective is to develop analytical (or semi-analytical), large-scale, integrated stratigraphic models, i.e. models that use time-averaged versions of underlying transport equations, to predict the evolution of continental margins on geologic time scales. In this context, we have followed two approaches in our EuroSTRATAFORM research program: (1) to conduct experiments in our subsiding-floor experimental basin that can be used to test, inform, and refine stratigraphic models in general, and (2) to contribute to the development of large-scale coupled, moving-boundary stratigraphic models. Our overall experimental objective is to assemble a group of experimental data sets from which we can measure the response of margin systems to a range of combinations of forcing parameters (e.g. sea level, sediment supply). Our overall modeling objective is to develop physically-based models that can be used to predict stratigraphic geometry, including grain size and facies, in response to imposed variation in the main forcing variables (sea level, subsidence, and sediment supply), as well as fulfill two basic needs of the larger margin modeling efforts: first, by providing estimates of the quantity and size distribution material delivered to the shoreline, and secondly by modeling the development of incised valleys and other large-scale stratal surfaces that are buried under marine sediments during marine transgression. Our fluvial models are formulated with the idea that they should work alone, or as modules in more complex margin models developed in concert with other EuroSTRATAFORM investigators.

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14. ABSTRACT
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APPROACH

One of the main focus areas identified in the EuroSTRATAFORM planning document is the dynamic response of the continental margin to changes in sea level (task D4). While field studies are relevant to this, it is practically impossible to observe the processes that control large-scale stratigraphic geometry in real time in the field. Thus, some amount of inference is required in order to understand and accurately interpret the depositional history and patterns we observe in the field with the processes and events that produced them. Our approach has been to use both laboratory experimentation and analytical/numerical modeling to help understand the controls on large-scale stratigraphic geometry. Controlled experiments provide well constrained data sets that can be used to test stratigraphic models. Conversely, physically-based analytical or numerical stratigraphic models provide general frameworks for understanding fundamental patterns or behaviors, and present the advantage that could be easily used for testing and predicting the outcomes of different combinations of hypothetical (but realistic) parameter scenarios and boundary conditions. The experimental work reported has been developed in our experimental basin (the EXperimental EarthScape or XES basin, known informally as "Jurassic Tank") equipped with a programmable subsiding floor [*Paola et al.*, 2001]. Our research efforts during the present year, however, have been focused mainly on the development of theoretical models on the long term evolution of depositional fluvial basins.

As mentioned, our modeling efforts are focused in formulating analytical, large-scale, integrated stratigraphic fluvial models based on fundamental physical processes: particularly channel-floodplain interaction and downstream sediment sorting. In our models we have included a diffusion-based description of the mean-surface dynamics [*Paola*, 2000] and first-order processes in channel belts and distal floodplains, aimed at predicting the long-term laterally averaged fractions of channel-belt versus floodplain deposits, for different conditions of downstream sedimentation rates (subsidence). Additionally, we have worked on developing a general solution for the problem of channel sorting considering sediment mass balances in channels, based on a formulation analogous to that presented in Paola and Seal (1995).

Our ongoing analytical modeling efforts are developed in close collaboration with other EuroSTRATAFORM PIs., principally Michael Steckler (SEQUENCE model), James Syvitski, and John Swenson (moving-boundary framework in shoreline/margin evolution models).

WORK COMPLETED

Experimental work: Our major experimental accomplishment so far has been to run an experiment on continental-margin stratigraphic response to sea-level changes. The experimental motivation, design and major results have been reported in the previous fiscal year.

Theoretical work: Firstly, we developed a heuristic formulation that can be used to predict the downstream variation of the laterally-averaged fractions of channel-belt versus floodplain deposits, for different subsidence patterns. The model scheme is based on three different time-scale ranges in fluvial-basin evolution: first, a short-time scale related to sediment transport and deposition within channels and channel-formation processes; secondly, an intermediate-time scale associated with sedimentation and superelevation of channel-belts; and finally, a long time scale associated with the laterally averaged evolution of the basin as channel belts swing across due to avulsions. This is ultimately a consequence of the interplay between the rate at which available space for deposition is created, and the differential rate of vertical accretion between channel belts and distal floodplains. The main equations used in the model are summarized below:

Short-term (channel): $$C_o B_{ch}\left[\frac{\partial \eta}{\partial t}_{ch} + \sigma\right] = -\frac{\partial}{\partial x}\left(I q_{sch} B_{ch}\right)$$

Mid-term (channel-belt): $$C_o B_{cb}\left[\frac{\partial \eta}{\partial t}_{cb} + \sigma\right] = -\frac{\partial}{\partial x}\left(I q_{sch} B_{cb}\beta\right) = r_{cb}$$

Long-term (alluvial basin): $$C_o B_v F_c\left[\left\langle\frac{\partial \eta}{\partial t}\right\rangle + \sigma\right] = r_{cb}$$

$$C_o\left(1 - F_c\right)\left[\left\langle\frac{\partial \eta}{\partial t}\right\rangle + \sigma\right] = -\left\langle q_w\right\rangle\frac{\partial C_{wl}}{\partial x} = r_{df}$$

where B_{ch}, B_{cb} and B_v are channel width, channel-belt width and basin width, respectively; I is an intermittency factor, β is the ratio of channel width to channel-belt width; σ is the subsidence rate; r_{cb} is the channel-belt sedimentation rate; r_{df} is the sedimentation rate in distal floodplain; F_c is the fraction of cross-section basin occupied by channel-belt deposits (sand); C_{wl} is the concentration in washloads. Long-term time averaging is indicated by brackets. Also, the average number of avulsions N is a function of the ratio:

$$N = 5\left(\frac{r_{cb}}{r_{df}} - 1\right)$$

Additionally,

$$r_{fp} = \frac{\alpha h}{T} C_{wl} \qquad \text{and} \qquad F_c = 1 - \exp(\varepsilon N)$$

In the above last equations, the proportion 5 indicates an average ratio between maximum scours in the channel and channel depth, αh is an average flooding depth in distal floodplains, taken as a proportion of the local channel depth h, T is a flooding frequency, and ε is the ratio of channel-belt to basin widths. The algorithm that predicts the downstream variation of the cross-basin averaged fractions of channel deposits has been already included into Steckler's SEQUENCE model.

We have also formulated an initial solution of the general problem of channel-driven downstream fining that assumes self-similar forms for the final substrate grain-size distribution, and that uses a mobility function that summarizes known effects of selective transport, for a given transport process (i.e. bedload or suspension). The differential transportability is expressed in terms only of size relative to the local mean size and variance of the sediment in transport, and the solution is developed on the following assumptions: (1) observed tendency to maintain constant dimensionless shear stress within channels [*Parker et al., 1998*], (2) size distribution of sediment supplied to a given reach (sorting cannot operate unless there is a range of sizes present), and (3) rate of sediment extraction by deposition (sorting by selective deposition cannot operate if there is no deposition). The governing equation is the Exner sediment mass balance for mixtures [*Paola and Seal, 1995*] and the similarity

variable $\xi = D - \overline{D} / \sigma_s$ is expressed in terms of the local mean sediment size $\overline{D}$ and standard deviation of local sediment size distribution σ_s. Besides predicting the final substrate size distribution as a function of the similarity variable ξ, the model also gives analytical expressions for the downstream changes in the mean size and variance, as functions of deposition rates.

RESULTS

The basin model outlined above has been adapted for inclusion in Mike Steckler's SEQUENCE model. Figure 1 shows results from a newer version of Steckler's SEQUENCE model that includes our fluvial sorting algorithms. Figure 1a shows SEQUENCE predictions of the downstream variation of the cross-basin averaged fractions of sand (channel belt deposits), F_c. Here, only two grain sizes were considered for the calculations, i.e. sand for channel belt deposits and mud for floodplain deposits, along the fluvial basin. Figure 1b shows SEQUENCE's predictions of the mud and sand distributions along the entire fluvial-continental margin system, for an arbitrary cycle of the sea-level change and constant sediment input.

(a) **(b)**

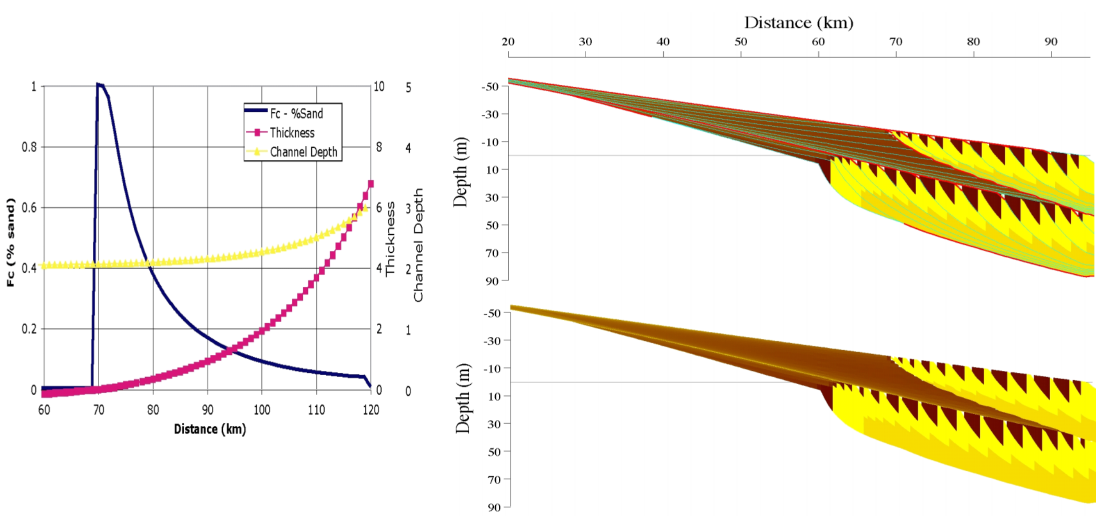

Figure 1: Theoretical results: Predictions from Steckler's SEQUENCE model after including our algorithm for downstream variation of the cross-basin averaged fractions of channel deposits F_c. (a) Computed downstream changes in the fractions of sand (channel-belt deposits) within the fluvial system, for a given pattern of subsidence (a surrogate of this is given in the figure by the thickness of the deposit); and (b) computed fractions of sand (yellow) and mud (brown) using SEQUENCE and our algorithm for the entire fluvial-margin system, for a cycle of the sea-level variation.

Our similarity solution for the problem of channel-driven downstream fining has been tested by using detailed hydraulic numerical models, for the cases of gravel and sand. Figure 2a shows the analytical solution for the long-term final substrate grain-size distribution (sand), and Figure 2b presents computed substrate size distributions at different downstream locations in the fluvial basin, using a detailed hydraulic model [*Wright, 2003*], run for 5000 years, for the case of a low-gradient, sand bed river for which sediment is transported mainly in suspension. According to this (Figure 2b), our

simplified similarity treatment forms a good first approximation for estimating channel sorting on long time scales.

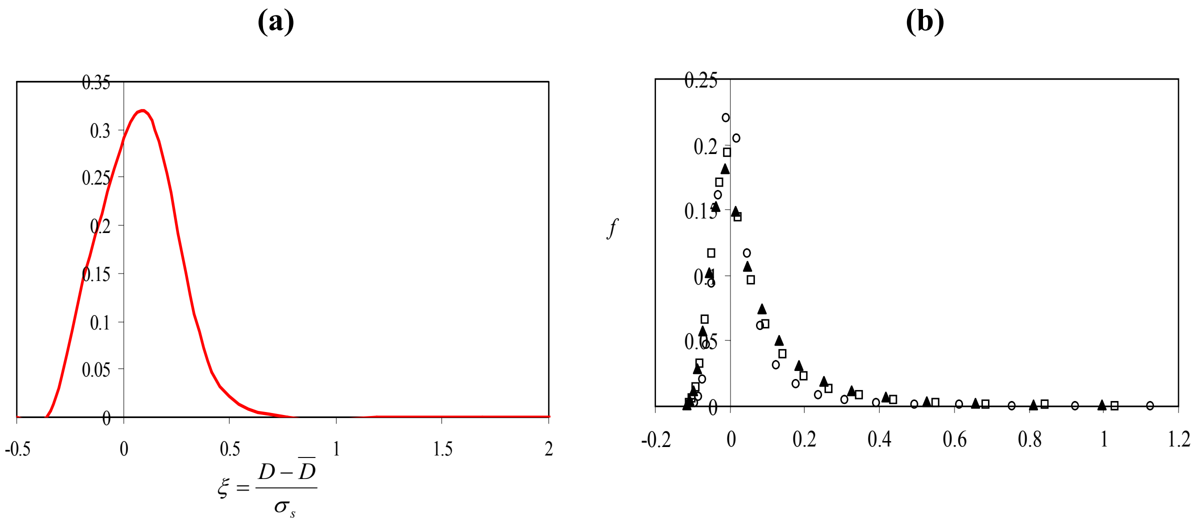

Figure 2: Self-similar solution for the (long-term) substrate grain-size distribution, f. (a) Analytical solution. (b) Approximately self-similar substrate grain-size distributions f, for different locations (x*= 0.3; 0.6 and 0.9, where the dimensionless downstream distance x* has been normalized using a characteristic basin length), computed using a detailed hydraulic model (Wright, 2003) for the case of downstream increasing rate of deposition, after 5000 years.

IMPACT/APPLICATIONS

The overall impact of our research will be in providing a means of testing stratigraphic models that goes beyond showing that they can only reproduce observed stratal columns without knowing whether the parameter sets used to do this are actually correct. The XES experimental program should provide new insight and data on how processes average across time scales to produce stratigraphy. Our physically-based theoretical models represent a first attempt to formally integrate mean-surface dynamics and first principles describing the interaction of channels and floodplain for analyzing the effects of externally-forced mechanisms (such as subsidence or sediment and water supply) on the resulting stratigraphic patterns in alluvial basins.

TRANSITIONS

Data from the XES experiments has already been shared with Lincoln Pratson and will be shared with other EuroSTRATAFORM colleagues. We are also continuing our collaborative modeling efforts with Mike Steckler. Our modeling work is now aimed at refining our formulations of downstream fining and, principally fluvial basin stratigraphic evolution, for a wider range of time-variable forcing, such as sediment supply or sea level changes.

RELATED PROJECTS

The EuroSTRATAFORM research we develop is performed within the framework of our new NSF Science and Technology Center (STC), the National Center for Earth-surface Dynamics (NCED) as well. NCED includes major research focus areas in basin dynamics as well as scaling processes across time and space and

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